



THE UNIVERSITY *of* EDINBURGH

Edinburgh Research Explorer

Testing inferences from palaeocurrents

Citation for published version:

Kirstein, LA, Carter, A & Chen, Y-G 2010, 'Testing inferences from palaeocurrents: application of zircon double-dating to Miocene sediments from the Hengchun Peninsula, Taiwan', *Terra nova*, vol. 22, no. 6, pp. 483-493. <https://doi.org/10.1111/j.1365-3121.2010.00970.x>

Digital Object Identifier (DOI):

[10.1111/j.1365-3121.2010.00970.x](https://doi.org/10.1111/j.1365-3121.2010.00970.x)

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Peer reviewed version

Published In:

Terra nova

Publisher Rights Statement:

Published version is available online at www.interscience.wiley.com copyright of Wiley-Blackwell (2010)

General rights

Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact openaccess@ed.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.



Author Final Draft or 'Post-Print' Version. The final version was published in Terra Nova available online. Copyright (2010) Wiley-Blackwell.

Cite As: Kirstein, LA, Carter, A & Chen, Y-G 2010, 'Testing inferences from palaeocurrents: application of zircon double-dating to Miocene sediments from the Hengchun Peninsula, Taiwan' *Terra nova*, vol 22, no. 6, pp. 483-493.

Testing inferences from palaeocurrents: Application of zircon double-dating to Miocene sediments from the Hengchun Peninsula, Taiwan

Linda A. Kirstein¹, Andrew Carter² and Yue-Gau Chen³

¹School of GeoSciences, University of Edinburgh, West Mains Road, Edinburgh EH9 3JW (linda.kirstein@ed.ac.uk)

²School of Earth Sciences, Birkbeck College, University of London, London, WC1E 7HX, U.K. (a.carter@ucl.ac.uk)

³Department of Geosciences, National Taiwan University, No.1, sec. 4th, Roosevelt Road, Taipei 10617, Taiwan, ROC. (ygchen@ntu.edu.tw)

ABSTRACT

Detrital zircon provenance studies that combine low-temperature fission-track and high-temperature U-Pb single-grain age dating are powerful in constraining sediment provenance by documenting the tectono-thermal evolution of the sediment source(s). We apply these techniques to Miocene (12-6 Ma) sandstones of the Hengchun Peninsula, southern Taiwan which, based on diametrically opposite palaeocurrents, have a controversial provenance. U-Pb grain ages range from Miocene (8 Ma) to Archaean (2.5 Ga). Cretaceous thermal cooling is recorded by detrital zircon fission-tracks at Loshui and Lilongshan. Permian fission-track grain ages account for <33% of zircon ages from Loshui, while at Lilongshan Jurassic/Triassic grain ages account for 33-66% of all zircon fission-track ages. Minor (<12%) Miocene age components are detected in both formations. These new data suggest that the primary source of these Miocene sediments was similar. A simple model is proposed invoking sediment reworking in this complex tectonic setting.

Introduction and Rationale

Sandstone palaeocurrents are widely used to infer different sediment source areas but this is rarely tested. A case in point is on Taiwan where Miocene sandstones of the Hengchun Peninsula show highly variable palaeocurrent directions (Sung & Wang, 1986). These have been interpreted as transportation from the north-northwest, from the south-southeast and from west to east (Cheng et al., 1984; Sung & Wang, 1986; Chang et al., 2003). Previous proposals to explain the palaeocurrent data have ignored complex currents in the depositional environment and suggest either an exotic source of sediment to the south (e.g. Sung & Wang, 1986) or that one of the units (Loshui) has been rotated during emplacement (e.g. Chang et al., 2003). These sandstones form part of the developing accretionary wedge and it is widely known that the composition of accretionary wedge sandstones can be affected by plate tectonic processes juxtaposing terranes, by magmatic arc dissection, by local structure and by recycling of sediment in the accretionary complex (e.g. Critelli, 1993). In these active tectonic settings, which are commonly characterized by elongated basins along orogenic strike, currents may be repeatedly changing and deflected or reflected by submarine topography. As a result, the use of palaeocurrents from these sediments to reconstruct for example, tectonic rotation (e.g. Chang et al., 2003), can be misleading.

To highlight the importance of reconstructing palaeodrainage not just by palaeocurrent direction we characterise the source formation age structure and post-metamorphic exhumation history. Zircon is a relatively ubiquitous, robust detrital mineral that can be double dated using fission-track and U-Pb dating techniques. It has been widely applied to successfully discriminate between source area contributions and unravel hinterland evolution (Carter & Moss, 1999). To test whether the palaeocurrent data have any real significance in the dynamic environment of an evolving accretionary complex and to resolve debate as to the origin of the sandstone material we applied detrital zircon dating techniques to Miocene sandstones of the Hengchun Peninsula, southern Taiwan in which highly variable palaeocurrent directions have been measured (Sung & Wang, 1986).

Taiwan

The island of Taiwan is located at the boundary between the Eurasia Plate and the Philippine Sea Plate (PSP) (Figure 1). Subduction along the Manila Trench was initiated in the Oligocene/Miocene. The 4 km high Central Range of Taiwan, result from collision of the Luzon volcanic arc and South China continental margin since late Miocene – early

Pliocene times (Teng, 1987; Kirstein et al., 2010). The Hengchun Peninsula, southern Taiwan and offshore Hengchun Ridge form the present day accretionary prism, with accretionary wedge growth occurring both by frontal accretion, with sediments from the continental margin scraped up into the accretionary wedge (Liu et al., 2004), and by underplating (Fuller et al., 2006). Modern sands offshore southern Taiwan are lithic-rich and dominated by distinct geographic sources including the accretionary wedge, the Taiwan suture zone and the Luzon forearc basin (Yen & Lundberg, 2006). Deep sea canyons and channels together with submarine topography associated with subduction and collision influence sediment routing.

Miocene Formations Hengchun Peninsula

The Hengchun Peninsula includes the narrow southern-most segment of the Central Range and forms the southern tip of Taiwan (Figure 1). The lithologies include metamorphosed Miocene rocks with subordinate Pliocene sediments (Figure 2). The stratigraphy in the Hengchun region is complex and a number of stratigraphic schemes exist (e.g. Sung, 1991; Ho, 1999; Huang et al., 2006), here we combine the stratigraphy of Ho (1999) for the oldest formation with that of Huang et al. (2006) (Figure 2). The metamorphosed early Miocene Lushan Formation is the southwards extension of the Central Range (Ho, 1999) (Figure 1) and is structurally overlain by the middle to late Miocene Loshui and Mutan Formations (Huang et al., 2006).

Compositionally the mid Miocene Loshui (Loshui Formation) and mid/late Miocene Lilongshan sandstones (Mutan Formation) differ (Cheng et al., 1984) (Figure 2). The 1000 m thick Loshui sandstones generally contain less lithic grains and more quartz than the Lilongshan sandstones (Figure 2). Loshui grains are sub-angular to sub-rounded and quartz-rich, with locally high organic matter content (Figure 2). Igneous clasts vary in composition from andesite to rhyolite/granite. Loshui sandstones are classed as sub-arkosic arenites. Lilongshan sandstones are lithic arenites, rich in volcanic, sedimentary and meta-sedimentary lithic fragments (Figure 2). Several volcanic lithic fragments show textures consistent with rapidly quenched mafic lavas. Other fragments are silicic with feldspar phenocrysts in a cryptocrystalline matrix. Quartz, plagioclase, hornblende and calcite grains are evident, along with a number of fossil fragments. Chlorite has pseudomorphed volcanic glass although the original form is preserved. Combining the petrography and the available palaeocurrent directions, which in the Lilongshan sandstones are from the northwest and in

the Loshui sandstones from the southeast led some authors to propose (Cheng et al., 1984; Sung & Wang, 1986; Yen, 2003), distinct origins for these sandstones.

To test for distinct sources, samples were collected from key localities of Loshui and Lilongshan sandstones (Figure 2) and, where possible, zircon grains were double dated using a combination of low-temperature fission-track and higher temperature U-Pb dating methods (see Supplementary material A for details). The selected Loshui sandstones were medium to coarse-grained and deposited in mid Miocene times (~ 10-12 Ma; Sung, 1991). Sample LS3 was from the lower part of the sequence with obvious sedimentary structures. Sample LS1 was from the massive, upper part of the sequence. At Lilongshan, the sandstones were medium to coarse-grained with rounded to sub-angular mafic clasts. Sample LL1 is stratigraphically younger than sample LL2. Deposition of Lilongshan sandstones occurred between 11 and 6 Ma (Huang et al., 2006).

Previous thermochronology studies of Miocene sediments from the Hengchun Peninsula are limited by a lack of zircon in the samples. Where fission-track analyses of detrital zircons have been provided the number of grains analysed was < 10 or not reported (Yen, 2003; Huang et al., 2008) as a result data deconvolution to identify principal sources is not possible although Miocene and Cretaceous peak components were reported by Huang et al. (2008). To constrain potential sources more grain measurements are required. In addition, by coupling zircon fission-track (ZFT) and U-Pb dating techniques with petrology, the provenance can be further constrained by comparing formation ages with post metamorphic cooling histories.

Results

ZFT age data are reported in Tables 1 & 2, supplementary material DR Table 1 and Figure 3. Significant variance in single grain ages i.e. mixed age populations (Galbraith & Laslett, 1993) was detected in all samples. Deconvolution into grain-age populations was performed using the Binomfit program (Brandon, 1992). All samples have at least two significant grain-age populations (Table 2, Figure 3). At Loshui the majority of zircon grains (>60%) generate a Cretaceous peak component (Figure 3). LS3 from the base of the section has minor peaks in the Permian and Palaeocene, while LS1 also records input from a source with a Miocene cooling history (Table 2, Figure 3). Lilongshan sandstones record Miocene, Cretaceous, Jurassic and Triassic age components, with both samples dominated by Mesozoic grains (>85%; Table 2). In general ZFT grain ages from the Loshui and Lilongshan sandstones are remarkably similar and are dominated by grains which show

Cretaceous cooling. All ZFT grain ages are < 400 Ma with cooling ages as young as Late Miocene determined (Figure 3).

U-Pb dating of the same grains used for ZFT analysis yield crystallisation ages from Miocene through to Archaean (Table 1, Supplementary material Table DR2, Figure 4). U-Pb grain ages are not reported where the discordance between the uncorrected $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$ ages was >10% (Table 1). The majority of the U-Pb grain age populations record formation events throughout the Mesozoic and Late Palaeozoic (110 – 360 Ma), Early Palaeozoic (460 – 520 Ma), Proterozoic (750 – 980 Ma; 1600 – 1990 Ma) and Late Archaean (<2790 Ma), with some Miocene age grains (Table 1, Figure 4). >35% of the grains are Cambrian or older, while at Loshui ~30% of the grains have Cretaceous U-Pb ages (Table 1). All samples have some concordant ZFT and U-Pb ages, particularly from the Cretaceous and Miocene (Figure 4).

Discussion

South China margin

The geology of southeast China in particular the South China Block (SCB) which consists of the Yangtze Craton and Cathaysia (Figure 5) is dominated by a wide Mesozoic magmatic belt with intense igneous activity in the Jurassic and Cretaceous (Wong et al., 2009). Late Permian – Triassic granites are widespread in the SCB (Wang et al., 2005) (Figure 5). As a result of these tectono-thermal events a spectrum of zircon crystallisation and cooling ages from Archaean to Cretaceous are anticipated from southeast China, with major crust building events listed in Table 3.

Concordant zircon FT and U-Pb ages between 260-125 Ma and 19-8 Ma record rapidly cooled magmatic sources (Figure 4) consistent with observed pebbles of basalt, andesite, gabbro and granodiorites in the sediments (this study, Pelletier & Stephan, 1986). Potential magmatic sources, outside mainland China are listed in Table 4, including the Luzon arc, Penghu Islands, intraplate magmatism and also oceanic lithosphere from the South China Sea and PSP. Early Cretaceous (Late Yenshanian) volcanism was widespread along the Chinese margin (Figure 5). Cretaceous grains originate from either rapidly cooled sources along the Chinese margin/proto-Taiwan (Figure 5) or from locally eroding old oceanic crust. The Loshui sandstones, which have most concordant ZFT and U-Pb Cretaceous grain-age components, contain primarily volcanic (andesite/dacite/rhyolite) lithic fragments. Early Cretaceous oceanic crust (131 – 119 Ma) is documented in the Huatung Basin and so erosion of the leading edge of the PSP cannot be discounted as a potential

source. Neogene intraplate magmatism in northwestern Taiwan occurred in the Early Miocene and Late Miocene (Table 4). The associated lithologies are basaltic and are not known to be zircon-bearing. South China Sea crust formed between 32 and 17 Ma and so cannot be the source of the young zircon grain-age component. Only the Luzon arc, which was initiated in the early Oligocene has zircon-bearing lithologies that crystallised during the necessary time interval.

Similar ZFT peak age components in the Miocene and Cretaceous are identified at Loshui and Lilongshan which suggests a similar tectono-thermal evolution for the grains. Older Permian ZFT peak age components were only detected at Loshui. These grains primarily have crystallisation ages that are Caledonian (c. 450-400 Ma) or older (Figure 4) and so may have cooled during subduction of the palaeo-Pacific Plate beneath South China in the Permian- Jurassic (Wong et al., 2009). Triassic and Jurassic ZFT grain-ages measured from Lilongshan have a similar range in crystallisation ages which suggests that no discrete, separate source region to the south need be invoked. However, the contribution of different sources varies with time, for example the Lilongshan sandstones have glassy magmatic fragments that have not travelled far since their original formation (Figure 2). These glassy fragments may well be sourced from the Penghu Islands but are not evident in the zircon analyses as the basaltic source rocks are not zircon bearing. The approach of coupling petrology with double dating of zircons from the detrital record highlights the importance of sediment recycling in this dynamic environment.

Depositional environment

The Hengchun Peninsula is today one of the principal morpho-tectonic units in the domain of incipient continental subduction, while the region of oceanic subduction is located south of 21°N (Malavieille & Trullenque, 2009). Turbidite deposition of sand-rich units directed along sub-marine canyons and channels into a complex system of basins is documented on both sides of the accretionary prism (Lundberg et al., 1992). Petrology and thermochronology data from the preserved sediment pile in the Hengchun Peninsula indicate that an equally complex sediment routing system may have operated in the Miocene during the progression from oceanic subduction to ocean-continent subduction, pre arc-continent collision. The Chinese continental margin, local magmatic centres and oceanic crust were potentially significant sediment sources (Figure 6). The majority of the U-Pb and ZFT grain-age distributions from Loshui and Lilongshan suggest sediment was originally sourced from southeast China. The origin of the Cretaceous grain-age component is debatable but the

occurrence of gabbroic clasts argues in favour of some localised erosion of the leading edge of the PSP, and is consistent with analogue modelling (Malavieille & Trullenque, 2009). Miocene grain-age components from Loshui and Lilongshan can only be sourced from the Luzon arc. This suggests that sediment from the forearc region was incorporated and mixed with sediment from the continental margin as collision progressed in the Miocene. In the North Luzon Trough sediment sourced from the rear slope of the accretionary prism is combined with forearc derived sediments (Yen & Lundberg, 2006) indicating the potential for localised mixing. While modern canyon systems, such as the Penghu Canyon, erode both the continental margin and accretionary wedge (Liu et al., 2004). In this complex submarine environment, topography, slope stability and channelling of sediment are constantly changing generating complex palaeocurrent directions. Such a dynamic environment facilitates localised reworking and mixing of sediment and highlights the potential for sediment reworking and mixing within marginal accretionary prism environments in the past.

Conclusions

Miocene sandstones preserved in the Hengchun Peninsula, southern Taiwan were sourced locally from the Chinese continental margin, proto-Taiwan, magmatic centres (Penghu Islands; Luzon arc) and oceanic lithosphere. The majority of the zircon grains preserve U-Pb ages consistent with original source material from southeast China. ZFT grain-age components are related to major tectonic events in the SCB, connected to subduction of the palaeo-Pacific Plate. Significantly the ZFT ages, together with the petrography, suggest that the Luzon arc and leading edge of the PSP were actively eroding in the Miocene.

Loshui sandstones have not been rotated through 180 ° as previously proposed (Chang et al., 2003) nor do they originate from an exotic terrane to the south (e.g. Yen, 2003). Instead sediment deposition in the Miocene was strongly controlled by structural trends, crustal deformation and erosion in and around the developing accretionary prism. The different palaeocurrent directions preserved in the Loshui and Lilongshan sandstones reflect reworking of sediment in this chaotic environment. Similar structural controls occur in the modern offshore region today (e.g. Lundberg et al., 1997) and along other active margins.

Acknowledgements

The editor, associate editor, S. Critelli and three anonymous reviewers are thanked for constructive comments. This work was supported by NERC grant NE/E012426/1.

References

- Brandon, M.T., 1992. Decomposition of fission-track grain-age distributions. *Amer. Jour. Sci.*, **292**, 535-564.
- Carter, A. and Moss, S.J., 1999. Combined detrital-zircon fission-track and U-Pb dating: A new approach to understanding hinterland evolution. *Geology*, **27**, 235-238.
- Chang C.-P., Angelier J.; Lee T.-Q., and Huang C.-Y., 2003. From continental margin extension to collision orogen: structural development and tectonic rotation of the Hengchun peninsula, southern Taiwan. *Tectonophysics*, **361**, 61-82.
- Chen, C. H., Chung, S.-H., Hwang, H.-H., Chen, C.-H., and Chung, S.-L., 2001. Petrology and Geochemistry of Neogene Continental Basalts and Related Rocks in Northern Taiwan(III): Alkali Basalts and Tholeiites from Shiting-Yinko Area. *West. Pac. Earth Sci.*, **19**, 19-46.
- Cheng, Y.-M., Huang, C-Y., Yeh, J-J., and Chen, W-S., 1984. The Loshui Formation: Deeper-water sandstones on the Hengchun Peninsula, southern Taiwan. *Acta Geol. Taiwan.*, **22**, 100-117.
- Chung, S-L., Yang, F.T., Lee, C-Y., and Chen, C-H., 1995. The igneous provinciality in Taiwan: consequence of continental rifting superimposed by Luzon and Ryukyu subduction systems. *Jour. South. Asian Earth Sci.*, **11**, 73-80.
- Critelli, S., 1993. Sandstone detrital modes in the Paleogene Liguride Complex, accretionary wedge of the Southern Apennines (Italy). *Jour. Sed. Petrol.*, **63**, 464-476.

- Deschamps, A., Monié, P., Lallemand, S., Hsu, S.K., and Yeh, K.Y., 2000. Evidence for Early Cretaceous oceanic crust trapped in the Philippine Sea Plate. *Earth Planet. Sci. Letts.*, **179**, 503-516.
- Dickinson, W.R., 1985. Interpreting provenance relations from detrital modes of sandstones. In: Provenance of Arenites, G.G. Zuffa, Ed., NATO ASI Series, **148**, 333–361.
- Fuller, C.W., Willett, S.D., Fisher, D., and Lu, C.-Y., 2006. A thermomechanical wedge model of Taiwan constrained by fission-track thermochronometry. *Tectonophysics*, **425**, 1–24.
- Galbraith, R.F., and Laslett, G.M., 1993. Statistical models for mixed fission track ages. *Nucl. Tracks Rad. Meas.*, **21**, 459-470.
- Ho, C.-S., 1999. An introduction to the geology of Taiwan: Taiwan, Central Geological Survey, 192 p.
- Hsu, S.K., Yeh, Y., Doo, W.B., and Tsai, C.H. , 2004. New bathymetry and magnetic lineations identifications in the Northernmost South China Sea and their tectonic implications. *Mar. Geophys. Res.*, **25**, 29-44.
- Huang, C.Y., Yuan, P.B., and Tsao, S.H., 2006. Temporal and spatial records of active arc-continent collision in Taiwan: A synthesis. *Geol. Soc. Am. Bull.*, **118**, 274–288.
- Huang, C.-Y., Chien, C-W., Yao, B., and Chang, C-P., 2008. The Lichi Mélange: A collision mélange formation along early arcward backthrusts during forearc basin closure, Taiwan arc-continent collision. In: Draut, A.E., Clift, P.D., Scholl, D.W., ed., Formation and Applications of the Sedimentary Record in Arc Collision Zones, *Geol. Soc. Am. Spec. Paper*, **436**, 127-154.
- Jahn, B.M., Zhou, X.H., and Li, J.L., 1990. Formation and tectonic evolution of Southeastern China and Taiwan: Isotopic and geochemical constraints. *Tectonophysics*, **183**, 145-160.

- Kirstein, L.A., Fellin, M.G, Willett, S.D, Carter, A.C, Chen, Y-G, and Lee, D-C., 2010. Onset of rapid erosion in Taiwan during the Late Pliocene constrained by detrital thermochronology. *Basin Res.*, **22**, 270-285 doi: 10.1111/j.1365-2117.2009.00426.x.
- Liu, C.-S., Huang, I.L. and Teng, L.S., 1997. Structural features off southwestern Taiwan. *Mar. Geol.*, **137**, 305-319.
- Liu, C.-S., Deffontaines, B., Lu, C-Y. and Lallemand, S., 2004. Deformation patterns of an accretionary wedge in the transition zone from subduction to collision offshore southwestern Taiwan. *Mar. Geophys. Res.*, **25**, 123-137.
- Lundberg, N., Reed, D.L., Liu, C.-S. and Lieske, J., 1997. Forearc-basin closure and arc accretion in the submarine suture zone south of Taiwan. *Tectonophysics*, **274**, 5-23.
- Malavieille, J. and Trullenque, G., 2009. Consequences of continental subduction on forearc basin and accretionary wedge deformation in SE Taiwan: Insights from analogue modelling. *Tectonophysics*, **466**, 377-394.
- Pelletier, B. and Stephan, J.F., 1986. Middle Miocene obduction and late Miocene beginning of collision registered in the Hengchun Peninsula: Geodynamic implications for the evolution of Taiwan. *Tectonophysics*, **125**, 133-160.
- Richard, M., Bellon, H., Maury, R., Barrier, E. and Wen-Shing, J., 1986. Miocene to recent calc-alkalic volcanism in eastern Taiwan: K-Ar ages and petrography. *Tectonophysics*, **125**, 87-102.
- Sung, Q., 1991. Explanatory text of the geological map of Taiwan, Hengchun Peninsula. Central Geological Survey, MOEA, 1-61.
- Sung, Q. and Wang, Y., 1986. Sedimentary environments of the Miocene sediments in the Hengchun Peninsula and their tectonic implications. *Mem. Geol. Soc. China*, **7**, 325-340.
- Teng, L.S., 1987. Tectonostratigraphic facies and geologic evolution of the Coastal Range, eastern Taiwan. *Mem. Geol. Soc. China*, **8**, 229-250.

Wang Q., Li J.-W., Jian P., Zhao Z.-H., Xiong X.-L., Bao Z.-W., Xu J.-F., Li C.-F., and Ma J.-L., 2005. Alkaline syenites in eastern Cathaysia (South China): link to Permian-Triassic transtension. *Earth Planet. Sci. Letts.*, **230**, 339-354.

Wong J., Sun M., Xing G., Li X.-h., Zhao G., Wong K., Yuan C., Xia X., Li L., and Wu F., 2009. Geochemical and zircon U-Pb and Hf isotopic study of the Baijuehuajian metaluminous A-type granite: Extension at 125-100 Ma and its tectonic significance for South China. *Lithos*, **112**, 289-305.

Yen, J.Y., 2003. Provenance of Miocene sedimentary sequences in the Hengchun Peninsula, southern Taiwan, and implications for the modern Taiwan orogen, Florida State University, 132 p.

Yen, J.-Y. and Lundberg, N., 2006. Sediment compositions in offshore southern Taiwan and their relations to the source rocks in modern arc-continent collision zone: *Mar. Geol.*, **225**, 247-263.

Yu, S.-B., Chen, H.-Y. and Kuo, L.-C., 1997. Velocity field of GPS stations in the Taiwan area. *Tectonophysics*, **274**, 41-59.

Yu, H.-S. and Song, G.-S., 1993. Submarine physiography around Taiwan and its relation to tectonic setting. *Jour. Geol. Soc. China*, **36**, 139-156.

Figures

Figure 1. Generalised tectonic and stratigraphic map of Taiwan with, from west to east, the geological divisions include: the Coastal Plain (CP), Western Foothills (WF), Central Range (Hsuehshan Range (HR), Backbone Slates (BS) & Tananao Complex (TC)), Longitudinal Valley (LV) and Coastal Range (CoR). Hengchun Peninsula (HP), volcanic rocks in the north-west (V). Submarine topography offshore of southern Taiwan includes a number of north-south trending submarine ridges and troughs (Hengchun Ridge; Southern Longitudinal Trough (SLT); Huatung Ridge; Taitung Trough (TT); Lutao-Lanshu Ridge) (Yu & Song, 1993; Huang et al., 2006). Each of these large scale features has highly variable internal topography which influences sediment routing. Inset shows direction of plate motion from Yu et al. (1997) and position of Philippine Sea Plate relative to Eurasia and location of the Luzon arc.

Figure 1.

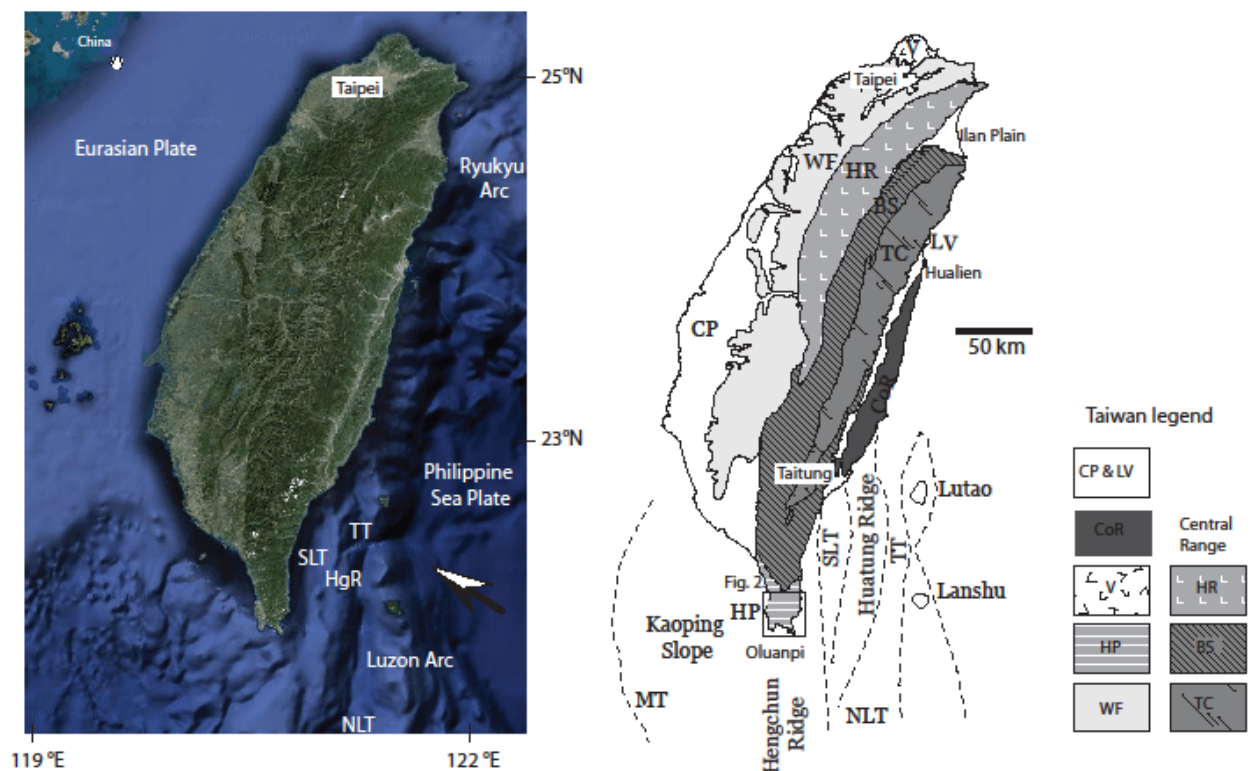


Figure 2. Enlarged map of part of the Hengchun Peninsula in which mid to late Miocene sandstones crop out, after Huang et al. (2006). Black squares sample sites for fission-track and U-Pb analyses. Mutan Formation includes the Lilongshan sandstones. Inset photomicrographs show Lilongshan lithic arenites (LL1) and Loshui sub-arkosic arenites (LS1). Quartz (q), plagioclase feldspar (p), alkali feldspar (a), volcanic lithics (v), meta-sedimentary lithics (s), volcanic glass (g), muscovite (m), calcite (c), amphibole (h). Palaeocurrent data from Cheng et al. (1984); Sung & Wang (1986) and Yen (2003). Quartz-feldspar-lithic ternary diagram after Dickinson (1985) illustrates lithic-rich nature of Lilongshan sandstones versus quartz-rich Loshui sandstones. Data from Sung & Wang (1986); this study.

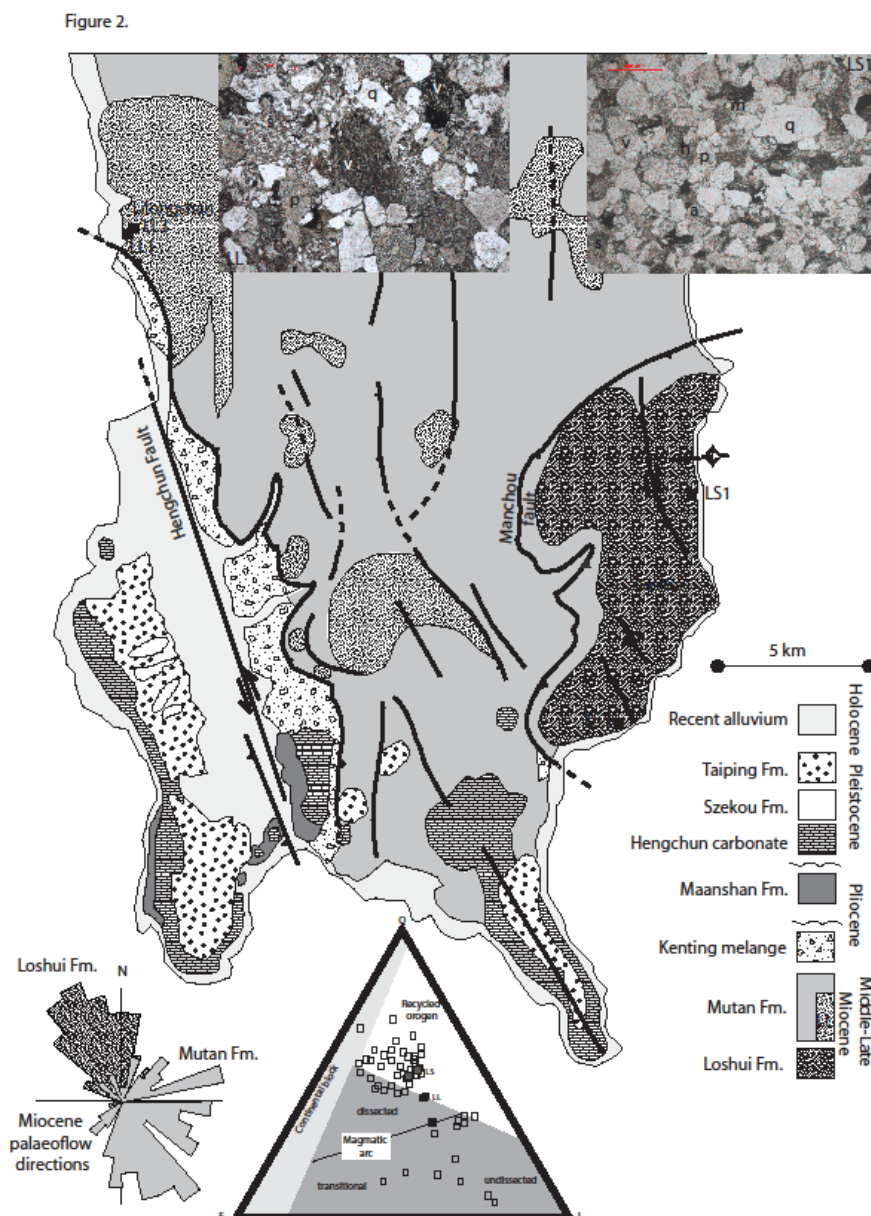


Figure 3. Detrital zircon fission-track grain age distributions from measured samples highlighting significant Cretaceous peaks. Samples LS from Loshui; LL from Lilongshan. Other peak age components range from Miocene through to Permian. Inset shows U-Pb grain age distributions which range from Miocene through to Archaean. Depositional age constraints from Sung (1991) and Huang et al. (2006).

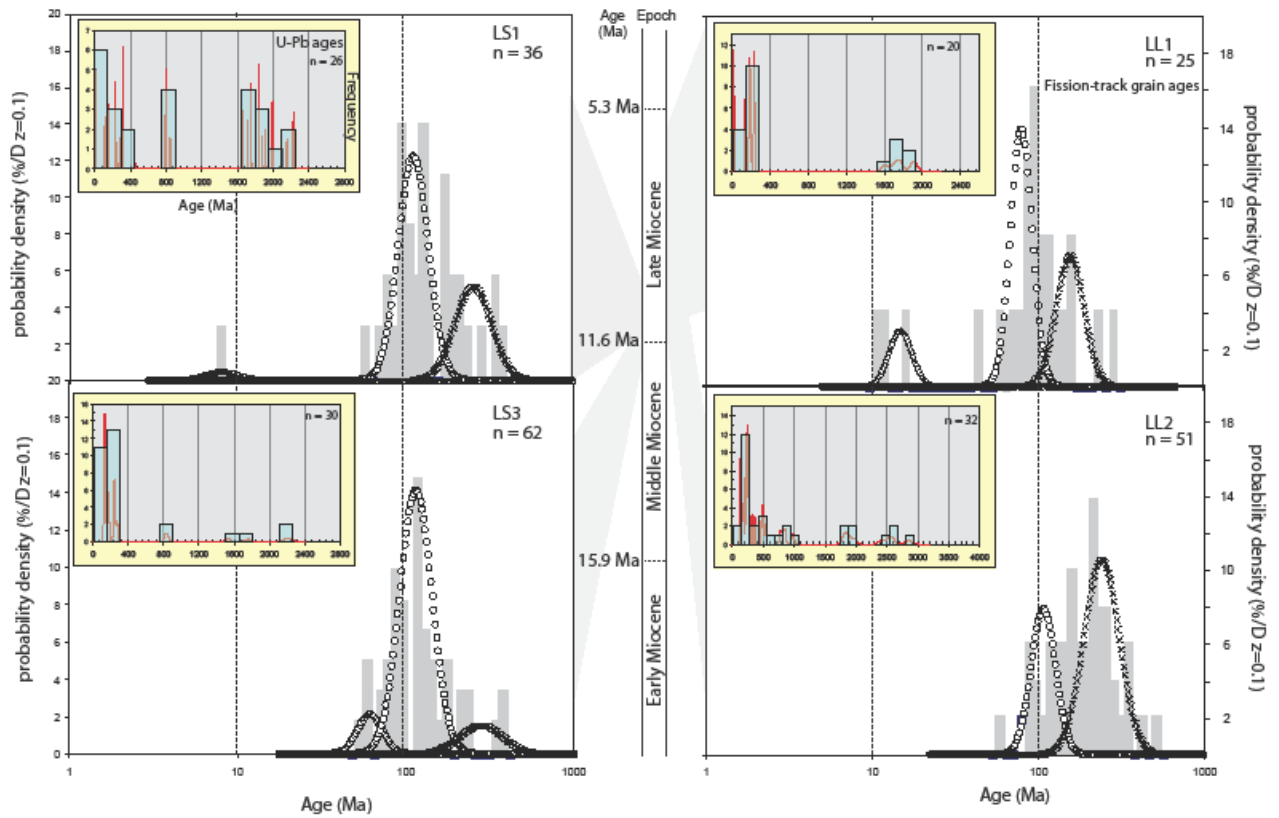


Figure 3.

Figure 4. Plot of zircon fission-track versus ^{238}U - ^{206}Pb grain ages for all samples analysed highlighting the sources of the grains dated. Major crust forming events affecting SE China labelled indicating that the majority of grains were originally sourced from southeast China. Dashed line shows concordant ZFT and U-Pb ages indicating rapidly cooled magmatic sources. Open diamonds LS3; filled diamonds LS1; open squares LL1; filled squares LL2.

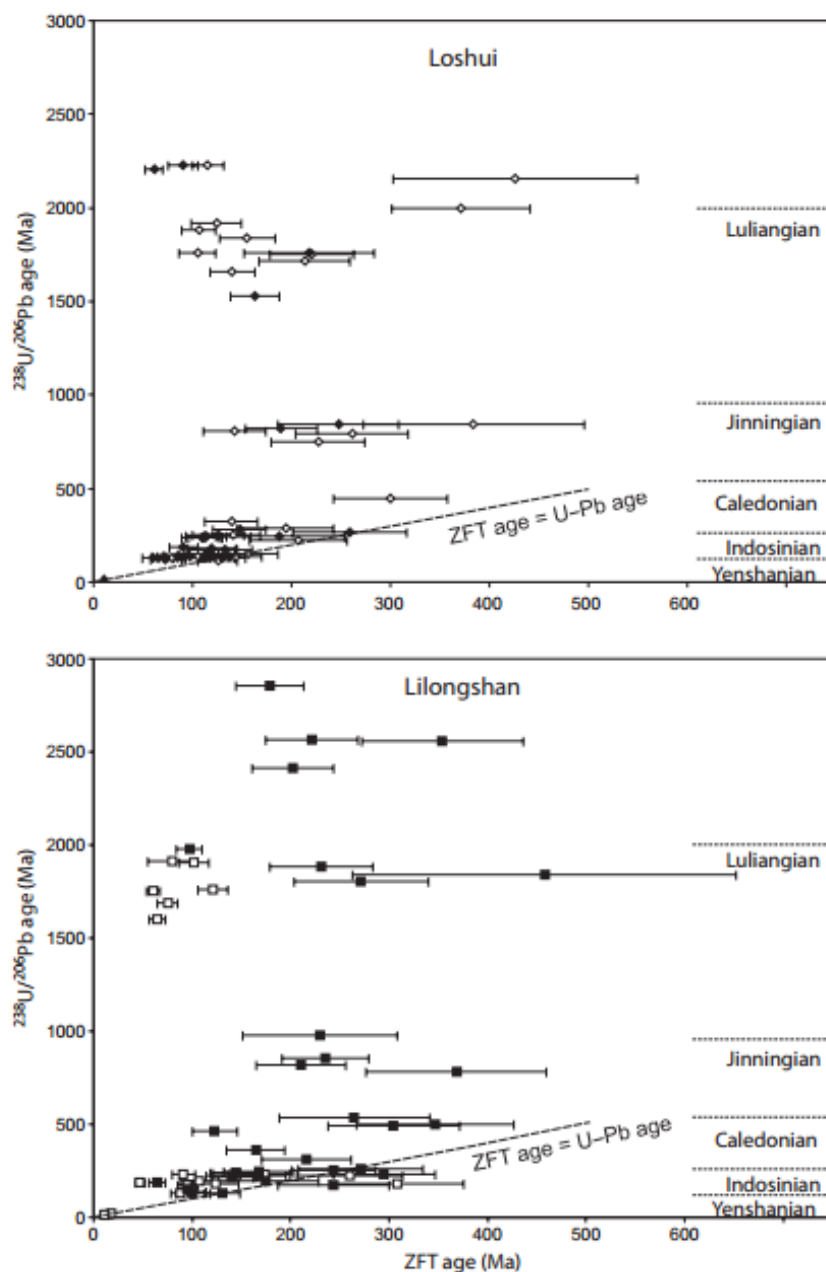


Figure 5. Schematic map of SE China showing the distribution of late Palaeozoic and Mesozoic intrusive and extrusive magmatic rocks after Wong et al. (2009); Wang et al. (2005). SCB = South China Block which includes both Cathaysia and Yangtze Craton basement.

Figure 5.

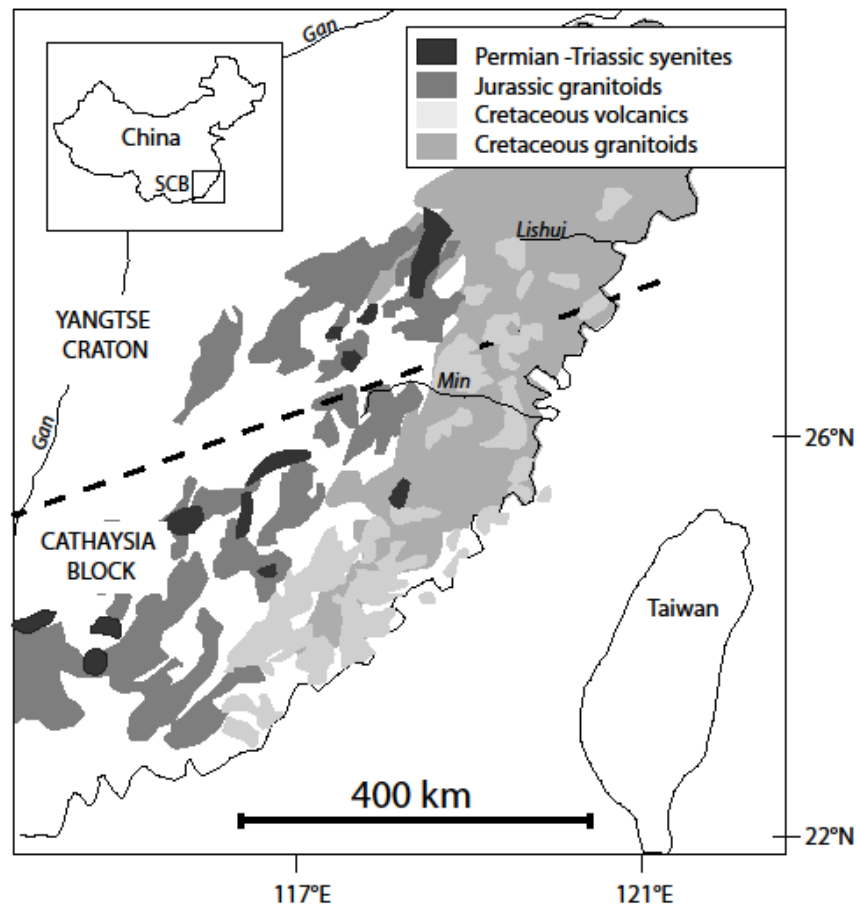


Figure 6. Reconstruction of the tectonic evolution of Taiwan at key stages during the deposition of the Hengchun Miocene sandstone units after Chung et al. (1995). Double-ended arrows indicate regions of extension. CSB – continental shelf break; BOS – base of slope; P – Penghu Islands intraplate magmatism; EP – Eurasian Plate; PSP – Philippine Sea Plate; LA – Luzon Arc; RT – Ryukyu Trench; MT – Manila Trench. Arrows indicate sediment pathways. Plate motion after Yu et al. (1987).

Figure 6.

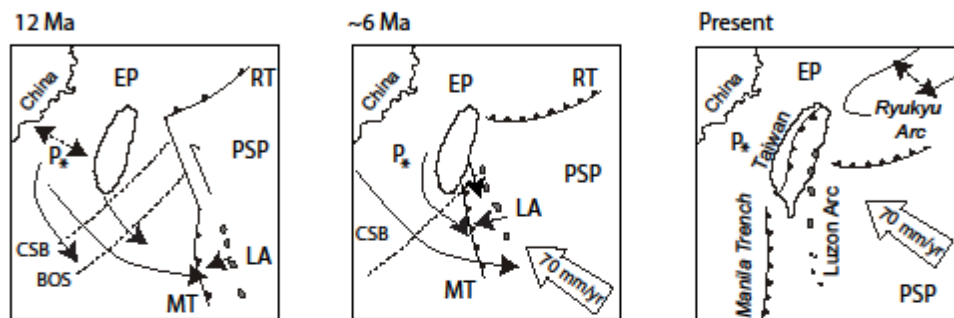


Table 1. Results from double-dating zircon grains using fission-track and U-Pb dating techniques.

Sample	crystal	Ns	Ni	U (ppm)	FT age (Ma)	\pm	Uncorrected ages (Ma)						% discordance
							$^{206}\text{Pb}/^{238}\text{U}$	$\pm 2\sigma$	$^{207}\text{Pb}/^{235}\text{U}$	$\pm 2\sigma$	$^{207}\text{Pb}/^{206}\text{Pb}$	$\pm 2\sigma$	
LS1	1	244	31	177	300	57	446.2	4.3	444.1	23.3	626.1	30.5	-0.5
	2	153	38	290	155	28	1839.3	0.8	1849.7	107.1	1855.2	11.5	0.6
	3	150	58	332	100	16							
	4	80	16	122	192	53							
	5	98	48	183	79	14	127.5	1.7	138.3	8.3	408.6	47.9	7.8
	6	147	13	99	427	124	2156.7	3.0	2113.9	409.0	2260.8	17.2	-2.0
	7	138	60	275	89	14							
	8	182	50	286	140	23	1658.2	1.5	1735.0	91.6	1870.6	11.5	4.4
	9	43	27	155	62	15							
	10	149	54	412	107	17	1879.8	2.7	1911.9	132.1	2024.8	11.6	1.7
	11	304	31	118	372	70	1994.2	1.3	1933.0	120.9	1917.2	11.4	-3.2
	12	184	32	122	221	42	1751.2	1.5	1778.3	107.6	1846.9	11.8	1.5
	13	164	24	137	261	57	792.5	1.6	786.8	32.2	819.6	17.8	-0.7
	14	103	32	244	124	25	1916.8	2.2	1809.7	203.5	1883.6	14.8	-5.9
	15	130	36	275	139	26	322.6	0.7	321.5	12.9	400.4	27.8	-0.3
	16	111	59	270	73	12							
	17	160	27	155	227	47	750.8	1.3	741.6	32.8	836.8	19.1	-1.2
	18	123	45	258	106	18							
	19	117	32	147	141	28	250.4	3.4	255.5	10.3	343.7	29.6	2.0
	20	82	40	305	79	15							
	21	106	41	313	100	18							
	22	139	25	143	213	46	1713.2	1.8	1629.9	126.5	1666.1	13.9	-5.1
	23	31	149	682	8	2	7.2	0.9					
	24	96	26	149	142	32	805.9	0.7	850.5	53.6	1152.0	22.0	5.2
	25	224	75	343	115	16	2227.6	1.5	2231.6	147.0	2261.4	10.7	0.1
	26	130	35	160	143	27	135.1	0.7	130.6	7.7	163.5	49.0	-3.5
	27	122	45	258	105	18	1758.3	1.0	1759.8	95.6	1841.3	11.6	0.1

Sample	crystal	Ns	Ni	U (ppm)	FT age (Ma)	±	²⁰⁶ Pb/ ²³⁸ U	± 2σ	Uncorrected ages (Ma)	²⁰⁷ Pb / ²³⁵ U	± 2σ	²⁰⁷ Pb/ ²⁰⁶ Pb	± 2σ	% discordance
	28	134	33	151	157	31	149.4	1.2	155.1	8.6	356.8	44.8	3.7	
	29	176	54	137	126	20	113.2	2.1	106.5	7.3	116.9	57.7	-6.4	
	30	90	33	189	106	22	138.2	0.9	148.5	8.9	357.6	48.5	6.9	
	31	96	19	109	194	49	289.1	2.8	305.3	20.8	580.7	47.0	5.3	
	32	132	13	74	384	112	846.1	2.8	828.5	44.7	943.2	20.5	-2.1	
	33	113	21	160	207	49	223.8	0.7	225.1	10.9	358.9	37.2	0.6	
	34	69	24	137	111	26								
	35	116	24	183	186	42								
	36	113	24	137	181	41								
LS3	1	96	42	160	89	16	127.5	5.6	123.8	11.0	138.7	82.4	-2.9	
	2	75	30	114	97	21	139.5	5.8	136.9	11.5	238.1	76.2	-1.9	
	3	110	45	294	95	17								
	4	105	33	189	123	25								
	5	131	56	427	91	15	2227.1	46.0	2314.6	138.8	2365.0	11.5	3.8	
	6	180	65	298	107	16								
	7	61	24	110	98	24								
	8	163	33	189	190	36	823.6	16.9	825.6	49.5	919.2	23.5	0.2	
	9	52	18	103	112	31	128.9	5.8	127.9	11.8	229.5	84.3	-0.8	
	10	145	43	246	130	23								
	11	109	35	200	120	23								
	12	94	32	163	114	23	136.0	5.7	151.6	11.7	469.7	66.0	10	
	13	126	50	286	98	16								
	14	103	30	137	133	28	174.4	6.0	173.9	11.6	299.0	56.9	-0.3	
	15	147	30	229	188	38								
	16	74	13	99	218	66	1760.8	35.4	1686.8	122.7	1757.3	13.9	-4.4	
	17	153	40	153	148	26	278.2	7.3	256.6	14.4	276.1	44.0	-8.4	
	18	186	72	275	100	14								
	19	110	37	169	115	22								
	20	68	11	42	237	77								

Sample	crystal	Ns	Ni	U (ppm)	FT age (Ma)	±	$^{206}\text{Pb}/^{238}\text{U}$	± 2σ	Uncorrected ages (Ma)	$^{207}\text{Pb}/^{235}\text{U}$	± 2σ	$^{207}\text{Pb}/^{206}\text{Pb}$	± 2σ	% discordance
	21	64	34	195	73	16	120.8	5.3	121.7	8.8		341.6	61.3	0.7
	22	85	39	223	84	16								
	23	156	23	105	259	58	269.4	7.3	258.5	15.9		356.4	47.8	-4.2
	24	139	46	211	117	20	141.2	5.4	142.6	7.6		257.5	41.0	1.0
	25	122	34	260	138	27	196.0	6.3	201.0	13.7		318.1	56.2	2.5
	26	68	23	59	114	28	150.0	6.3	146.7	15.3		396.5	95.8	-2.3
	27	55	25	143	85	21	135.2	6.4	139.5	16.6		494.2	107.9	3.1
	28	93	30	172	120	25	174.3	5.8	176.9	9.7		306.4	44.1	1.4
	29	66	16	122	159	44								
	30	105	38	290	107	20								
	31	62	19	145	126	33	247.6	6.9	262.5	14.0		472.1	40.2	5.7
	32	99	32	244	120	24	178.9	5.8	196.8	9.4		503.5	36.0	9.1
	33	147	50	254	114	19								
	34	47	4	23	443	231								
	35	224	53	303	163	25	1530.9	31.0	1654.0	86.2		1854.9	13.5	7.4
	36	114	40	122	110	20								
	37	76	36	275	82	17								
	38	90	26	198	134	30								
	39	120	41	313	113	21	241.6	6.7	244.4	11.8		300.3	37.3	1.1
	40	129	55	315	91	15	184.4	5.8	185.6	8.1		267.7	32.8	0.6
	41	49	10	57	188	65	246.6	7.3	241.4	16.0		385.2	52.3	-2.2
	42	101	31	142	126	26	252.0	7.5	253.2	17.9		377.7	55.4	0.5
	43	40	14	107	111	34								
	44	172	109	416	61	8								
	45	132	84	641	61	9	2203.4	46.7	2194.3	144.8		2216.7	12.8	-1.4
	46	77	50	382	60	11	131.8	5.4	134.5	7.6		213.9	44.3	2.1
	47	123	19	109	248	61	846.0	17.7	785.0	43.7		804.8	23.9	-7.8
	48	185	64	183	112	16	241.0	6.7	238.3	11.6		318.1	37.8	-1.1
	49	102	39	298	101	19								

Sample	crystal	Ns	Ni	U (ppm)	FT age (Ma)	±	²⁰⁶ Pb/ ²³⁸ U	± 2σ	Uncorrected ²⁰⁷ Pb / ²³⁵ U	ages (Ma) ± 2σ	²⁰⁷ Pb/ ²⁰⁶ Pb	± 2σ	% discordance
	50	87	47	154	72	13	138.9	5.6	143.1	9.9	268.6	58.4	2.9
	51	57	24	183	92	22	133.9	5.5	137.9	8.9	321.5	53.1	2.9
	52	111	39	223	110	21	236.1	6.6	237.6	6.6	297.7	33.1	0.6
	53	90	25	191	139	31							
	54	199	49	224	157	25							
	55	301	29	111	393	77							
	56	86	29	190	115	25							
	57	47	18	137	101	28							
	58	118	36	275	127	24							
	59	129	42	192	119	21							
	60	156	113	518	54	7							
	61	64	6	46	403	172							
	62	99	34	260	113	22							
LL1	1	145	40	305	140	25	226.1	5.4	234.5	8.5	306.8	28.8	3.6
	2	184	27	155	261	54	227.1	5.7	247.1	12.3	480.7	38.3	8.1
	3	45	136	623	13	2	12.2	3.3					
	4	119	37	188	124	23	183.4	4.9	187.0	8.6	199.6	39.1	1.9
	5	196	125	477	61	7	1755.6	34.9	1809.0	82.5	1881.5	11.4	3.0
	6	167	65	372	99	15	138.8	5.2	146.1	13.4	491.9	82.5	5.0
	7	118	45	206	102	18							
	8	161	83	380	75	10	1686.7	33.6	1772.3	82.7	1883.6	11.9	4.8
	9	166	99	453	65	8	1600.8	31.9	1716.4	85.5	1902.4	12.3	6.7
	10	246	108	412	88	10	133.7	4.4	147.5	8.6	465.4	50.1	9.3
	11	191	81	371	91	12	233.4	5.7	236.6	10.8	333.1	36.4	1.3
	12	262	58	266	174	25	232.0	5.7	249.2	11.8	462.2	36.4	6.9
	13	200	69	316	112	16							
	14	250	206	674	47	4	184.9	4.8	194.8	7.7	361.4	32.1	5.1
	15	152	34	156	172	33							
	16	130	289	662	18	2	18.9	3.3					

Sample	crystal	Ns	Ni	U (ppm)	FT age (Ma)	±	$^{206}\text{Pb}/^{238}\text{U}$	± 2σ	Uncorrected ages (Ma)	$^{207}\text{Pb}/^{235}\text{U}$	± 2σ	$^{207}\text{Pb}/^{206}\text{Pb}$	± 2σ	% discordance
	17	155	59	338	102	16	1906.9	39.5	1920.2	125.1		1967.3	12.8	0.7
	18	272	87	398	121	15	1758.3	36.0	1810.7	100.9		1873.3	13.0	2.9
	19	47	161	614	11	2	10.9	3.3	13.8	3.6				
	20	157	62	284	98	15								
	21	111	40	305	107	20	193.8	5.2	196.7	9.4		319.8	39.7	1.5
	22	134	35	200	148	28								
	23	186	23	88	308	68	178.5	5.0	180.3	9.2		343.3	43.0	1.0
	24	33	16	61	80	24	1912.1	41.5	1820.3	188.2		1891.0	16.0	-5.0
	25	326	132	378	96	10	173.1	4.9	169.1	8.5		190.8	43.5	-2.4
LL2	1	191	76	435	97	13	1976.9	39.1	1794.9	182.4		1785.9	15.3	-10
	2	97	14	107	265	76	537.3	10.5	521.2	25.7		580.3	27.3	-3.1
	3	128	18	41	272	69	1806.8	34.9	1782.9	155.7		1809.5	14.8	-1.3
	4	150	26	60	221	47	2567.9	52.9	2358.7	308.2		2345.4	13.7	-8.9
	5	60	10	38	230	79	980.9	20.7	891.4	78.4		998.3	29.4	-10
	6	286	37	141	295	52	230.2	5.9	227.6	12.0		242.2	41.3	-1.2
	7	244	72	236	131	18	131.3	4.5	129.5	6.3		136.8	37.8	-1.4
	8	124	39	223	123	23	462.6	9.2	451.7	18.3		456.7	25.2	-2.4
	9	150	40	229	145	26	237.6	5.7	236.6	8.9		241.7	28.3	-0.4
	10	137	25	114	210	46	817.9	15.7	760.6	37.6		762.3	22.2	-7.5
	11	59	13	74	175	54	193.8	5.5	179.9	10.7		194.5	50.4	-7.7
	12	152	27	124	216	45	313.8	7.3	296.1	16.3		312.4	40.4	-6.0
	13	192	24	137	305	66	492.2	10.8	524.9	30.6		777.2	31.3	6.2
	14	169	70	401	94	13								
	15	170	80	458	82	11								
	16	149	21	192	271	63	259.4	6.8	263.8	13.7		328.4	39.6	1.7
	17	175	18	103	369	91	779.1	15.8	775.8	42.3		889.1	22.7	0.4
	18	157	43	197	141	24								
	19	158	34	156	179	34	2857.2	63.0	2790.0	386.8		2833.0	11.5	-2.4
	20	74	23	176	124	30								

Sample	crystal	Ns	Ni	U (ppm)	FT age (Ma)	±	²⁰⁶ Pb/ ²³⁸ U	± 2σ	Uncorrected ages (Ma)		²⁰⁷ Pb/ ²⁰⁶ Pb	± 2σ	% discordance
	21	187	43	281	167	28	227.4	6.1	247.4	9.7	518.0	28.9	8.1
	22	62	14	128	171	51							
	23	175	31	237	217	42							
	24	153	29	133	203	41	2415.8	52.1	2328.0	261.6	2365.1	12.8	-3.8
	25	237	45	147	202	33							
	26	139	23	176	232	52	1886.9	39.9	1863.3	170.3	1831.5	15.3	-1.3
	27	150	53	347	109	18							
	28	135	35	267	149	28							
	29	192	21	160	347	80	498.0	10.5	474.1	21.4	477.9	27.6	-5.0
	30	434	178	679	94	9	155.6	5.2	168.8	6.8	384.3	28.9	7.8
	31	125	48	244	101	17	132.6	5.2	134.6	9.2	245.8	59.2	1.5
	32	86	18	118	184	48							
	33	140	22	168	244	56	172.5	5.6	176.0	9.2	290.7	42.7	2.0
	34	73	6	34	458	195	1841.9	43.9	1742.0	266.1	1802.7	23.2	-5.7
	35	177	30	137	226	45							
	36	183	110	630	65	8	187.5	5.6	188.1	7.6	171.1	31.0	0.3
	37	167	39	223	165	29	360.7	7.8	345.8	17.8	366.9	35.3	-4.3
	38	179	28	128	245	50							
	39	187	50	229	144	23	240.1	6.4	240.1	10.5	287.2	33.7	0.0
	40	126	29	166	167	35	243.5	6.8	257.8	14.8	465.8	43.5	5.5
	41	130	41	313	123	22							
	42	229	32	147	273	52							
	43	196	21	160	354	82	2554.9	57.8	2525.5	290.6	2519.1	15.1	-1.2
	44	242	38	218	244	43	251.2	6.6	258.9	11.2	358.9	32.6	3.0
	45	159	33	252	185	36							
	46	217	30	114	276	54							
	47	156	10	46	582	190							
	48	203	33	151	236	44	853.3	15.5	812.2	37.1	850.2	19.2	-5.1
	49	201	55	252	141	22	215.7	5.4	234.5	9.1	486.9	29.0	8.0

Sample	crystal	Ns	Ni	U (ppm)	FT age (Ma)	±	$^{206}\text{Pb}/^{238}\text{U}$	± 2σ	Uncorrected ages (Ma)	$^{207}\text{Pb}/^{235}\text{U}$	± 2σ	$^{207}\text{Pb}/^{206}\text{Pb}$	± 2σ	% discordance
	50	190	78	447	94	13								
	51	162	17	78	361	92								

Note only U-Pb ages where the percentage discordance is <10 are reported. In italics are young $^{206}\text{Pb}/^{238}\text{U}$ ages that equal the ZFT age but have a high % common Pb.

Table 2. Deconvoluted detrital zircon fission-track data

Sample	Long. (°)	Lat. (°)	No. grains	Grain age distribution (Ma)		Age dispersion $p\chi^2$ RE%		Depositional Age (Ma)	Age components (Ma)		
				Min	Max				1 st (Count)	2 nd (Count)	3 rd (Count)
LS1	120.891	22.085	36	8.2	412.5	0.0	67.8	11-10	8.1 (1)	113 (23)	257 (12)
LS3	120.865	21.995	61	53.5	398.9	0.0	32.2	12-11	61 (6)	116 (48)	282 (7)
LL1	120.709	22.144	25	11.5	302.8	0.0	76.5	11-6	14.8 (3)	80 (13)	157 (9)
LL2	120.710	22.145	51	64.4	556.4	0.0	43.2	11-6	107 (17)	239 (34)	

LS= Loshui; LL= Lilongshan; Zeta = 127±5

Table 3

Key tectonic events in the evolution of south-east China

<i>Event</i>	<i>Period (Ma)</i>	<i>Timing</i>
Late Yenshanian	142-67	Cretaceous
Early Yenshanian	180-145	Jurassic
Indosinian	250-200	Triassic
Caledonian	500-400	Ordovician-Devonian
Jinningian	980-770	Neo-proterozoic
Luliangian	2000-1800	Proterozoic

Sources: Jahn et al., 1990; Wang et al., 2005; Wong et al., 2009.

Table 4

Key magmatic occurrences in the region of Taiwan from Cretaceous to present.

<i>Source</i>	<i>Formation age (Ma)</i>
Intraplate Chiaopanshan stage	13 - 9
Luzon arc	29 - present
Magmatism, northern Taiwan	23 ± 2
Intraplate Kungkuan stage	23 - 20
Oceanic crust, South China Sea	37 - 15
Huayu (Penghu Islands)	61 - 65
Tananao Complex, arc magmatism	97 - 77
Oceanic crust, eastern Taiwan	< 131

Sources: Richard et al., 1986; Chung et al., 1995; Deschamps et al., 2000; Chen et al., 2001; Hsu et al., 2004; Chen et al., 2010.

Data repository item 2.

Table DR1. Detrital zircon fission-track age data for samples from Lilongshan and Loshui

Lilongshan: LL1

Longitude (°):	22.1448
Latitude (°):	120.7099
Stratigraphic age (Ma):	11-6
Effective track density for fluence monitor (tracks/cm ²):	6.14E+05
Relative error (%):	3.94E-02
Effective uranium content of monitor (ppm):	39
zeta factor & standard error (yr cm ²):	127 5
Size of counter square (cm ²):	1.39E-06

crystal	Ng	Ns	Ni	rho-s (tr/cm ²)	rho-i (tr/cm ²)	U (ppm)	age (Ma)	±
1	6	145	40	1.74E+07	4.81E+06	305.32	139.90	25.08
2	8	184	27	1.66E+07	2.44E+06	154.57	260.54	53.84
3	10	45	136	3.25E+06	9.81E+06	622.86	12.90	2.23
4	9	119	37	9.54E+06	2.97E+06	188.28	124.27	23.47
5	12	196	125	1.18E+07	7.52E+06	477.07	60.89	7.03
6	8	167	65	1.51E+07	5.86E+06	372.11	99.47	14.62
7	10	118	45	8.51E+06	3.25E+06	206.09	101.50	17.85
8	10	161	83	1.16E+07	5.99E+06	380.13	75.24	10.23
9	10	166	99	1.20E+07	7.14E+06	453.40	65.09	8.33
10	12	246	108	1.48E+07	6.49E+06	412.19	88.26	10.28
11	10	191	81	1.38E+07	5.84E+06	370.97	91.35	12.19
12	10	262	58	1.89E+07	4.18E+06	265.63	173.87	25.37
13	10	200	69	1.44E+07	4.98E+06	316.01	112.10	15.75
14	14	250	206	1.29E+07	1.06E+07	673.89	47.17	4.50
15	10	152	34	1.10E+07	2.45E+06	155.71	172.10	32.76
16	20	130	289	4.69E+06	1.04E+07	661.79	17.53	1.87
17	8	155	59	1.40E+07	5.32E+06	337.76	101.69	15.63
18	10	272	87	1.96E+07	6.28E+06	398.45	120.84	15.00
19	12	47	161	2.83E+06	9.68E+06	614.46	11.38	1.89
20	10	157	62	1.13E+07	4.47E+06	283.95	98.05	14.78
21	6	111	40	1.33E+07	4.81E+06	305.32	107.37	19.87
22	8	134	35	1.21E+07	3.16E+06	200.37	147.67	28.12
23	12	186	23	1.12E+07	1.38E+06	87.78	308.03	68.25
24	12	33	16	1.98E+06	9.62E+05	61.06	79.97	24.39
25	16	326	132	1.47E+07	5.95E+06	377.84	95.64	9.98

Lilongshan: LL2

Longitude (°):	22.1447
Latitude (°):	120.7089
Stratigraphic age:	11-6
Effective track density for fluence monitor (tracks/cm ²):	6.14E+05
Relative error (%):	3.94E-02
Effective uranium content of monitor (ppm):	39
zeta factor & standard error (yr cm ²):	127 5
Size of counter square (cm ²):	1.39E-06

crystal	Ng	Ns	Ni	rho-s (tr/cm ²)	rho-i (tr/cm ²)	U (ppm)	age (Ma)	±
1	8	191	76	1.72E+07	6.85E+06	435.08	97.31	13.28
2	6	97	14	1.17E+07	1.68E+06	106.86	264.80	75.81
3	20	128	18	4.62E+06	6.49E+05	41.22	271.63	68.50
4	20	150	26	5.41E+06	9.38E+05	59.54	221.24	47.12
5	12	60	10	3.61E+06	6.01E+05	38.17	229.94	78.62
6	12	286	37	1.72E+07	2.22E+06	141.21	294.73	51.69
7	14	244	72	1.26E+07	3.71E+06	235.53	130.88	17.67
8	8	124	39	1.12E+07	3.52E+06	223.27	122.87	22.64

9	8	150	40	1.35E+07	3.61E+06	228.99	144.67	25.84
10	10	137	25	9.88E+06	1.80E+06	114.50	210.33	45.86
11	8	59	13	5.32E+06	1.17E+06	74.42	174.68	53.59
12	10	152	27	1.10E+07	1.95E+06	123.66	215.98	45.23
13	8	192	24	1.73E+07	2.16E+06	137.40	304.79	66.16
14	8	169	70	1.52E+07	6.31E+06	400.74	93.51	13.37
15	8	170	80	1.53E+07	7.22E+06	457.98	82.38	11.24
16	5	149	21	2.15E+07	3.03E+06	192.35	271.04	63.31
17	8	175	18	1.58E+07	1.62E+06	103.05	368.57	91.41
18	10	157	43	1.13E+07	3.10E+06	196.93	140.90	24.35
19	10	158	34	1.14E+07	2.45E+06	155.71	178.80	33.91
20	6	74	23	8.90E+06	2.77E+06	175.56	124.32	29.74
21	7	187	43	1.93E+07	4.43E+06	281.33	167.47	28.44
22	5	62	14	8.95E+06	2.02E+06	128.24	170.50	50.52
23	6	175	31	2.10E+07	3.73E+06	236.62	216.56	42.33
24	10	153	29	1.10E+07	2.09E+06	132.82	202.62	41.15
25	14	237	45	1.22E+07	2.32E+06	147.21	202.27	33.04
26	6	139	23	1.67E+07	2.77E+06	175.56	231.57	52.25
27	7	150	53	1.55E+07	5.46E+06	346.76	109.48	17.58
28	6	135	35	1.62E+07	4.21E+06	267.16	148.75	28.31
29	6	192	21	2.31E+07	2.53E+06	160.29	347.18	79.97
30	12	434	178	2.61E+07	1.07E+07	679.34	94.43	8.53
31	9	125	48	1.00E+07	3.85E+06	244.26	100.81	17.19
32	7	86	18	8.86E+06	1.86E+06	117.77	183.76	47.71
33	6	140	22	1.68E+07	2.65E+06	167.93	243.61	55.99
34	8	73	6	6.58E+06	5.41E+05	34.35	458.01	194.64
35	10	177	30	1.28E+07	2.16E+06	137.40	226.17	44.79
36	8	183	110	1.65E+07	9.92E+06	629.73	64.58	7.85
37	8	167	39	1.51E+07	3.52E+06	223.27	164.93	29.44
38	10	179	28	1.29E+07	2.02E+06	128.24	244.71	49.87
39	10	187	50	1.35E+07	3.61E+06	228.99	144.29	23.08
40	8	126	29	1.14E+07	2.62E+06	166.02	167.32	34.56
41	6	130	41	1.56E+07	4.93E+06	312.96	122.53	22.03
42	10	229	32	1.65E+07	2.31E+06	146.55	273.32	51.75
43	6	196	21	2.36E+07	2.53E+06	160.29	354.22	81.51
44	8	242	38	2.18E+07	3.43E+06	217.54	243.79	42.70
45	6	159	33	1.91E+07	3.97E+06	251.89	185.29	35.56
46	12	217	30	1.30E+07	1.80E+06	114.50	276.20	53.97
47	10	156	10	1.13E+07	7.22E+05	45.80	581.58	189.93
48	10	203	33	1.46E+07	2.38E+06	151.13	235.64	44.38
49	10	201	55	1.45E+07	3.97E+06	251.89	141.03	21.57
50	8	190	78	1.71E+07	7.03E+06	446.53	94.34	12.77
51	10	162	17	1.17E+07	1.23E+06	77.86	361.46	92.32

LSI

Longitude (°):	22.0849
Latitude (°):	120.8906
Stratigraphic age:	11-10
Effective track density for fluence monitor (tracks/cm ²):	6.14E+05
Relative error (%):	3.94E-02
Effective uranium content of monitor (ppm):	39
zeta factor & standard error (yr cm ²):	127 5
Size of counter square (cm ²):	1.39E-06

crystal	Ng	Ns	Ni	rho-s (tr/cm ²)	rho-i (tr/cm ²)	U (ppm)	age (Ma)	±
1	8	244	31	2.20E+07	2.80E+06	177.47	299.99	57.38
2	6	153	38	1.84E+07	4.57E+06	290.06	155.20	28.23
3	8	150	58	1.35E+07	5.23E+06	332.04	100.12	15.56
4	6	80	16	9.62E+06	1.92E+06	122.13	192.18	52.71
5	12	98	48	5.89E+06	2.89E+06	183.19	79.17	14.00

6	6	147	13	1.77E+07	1.56E+06	99.23	426.72	123.65
7	10	138	60	9.96E+06	4.33E+06	274.79	89.11	13.85
8	8	182	50	1.64E+07	4.51E+06	286.24	140.47	22.53
9	8	43	27	3.88E+06	2.44E+06	154.57	61.84	15.21
10	6	149	54	1.79E+07	6.49E+06	412.19	106.76	17.04
11	12	304	31	1.83E+07	1.86E+06	118.31	371.67	70.31
12	12	184	32	1.11E+07	1.92E+06	122.13	220.52	42.37
13	8	164	24	1.48E+07	2.16E+06	137.40	261.23	57.23
14	6	103	32	1.24E+07	3.85E+06	244.26	124.37	25.24
15	6	130	36	1.56E+07	4.33E+06	274.79	139.37	26.33
16	10	111	59	8.01E+06	4.26E+06	270.21	72.99	11.81
17	8	160	27	1.44E+07	2.44E+06	154.57	227.15	47.39
18	8	123	45	1.11E+07	4.06E+06	257.62	105.77	18.50
19	10	117	32	8.44E+06	2.31E+06	146.55	141.09	28.23
20	6	82	40	9.86E+06	4.81E+06	305.32	79.49	15.38
21	6	106	41	1.27E+07	4.93E+06	312.96	100.09	18.47
22	8	139	25	1.25E+07	2.25E+06	143.12	213.35	46.46
23	10	31	149	2.24E+06	1.08E+07	682.40	8.11	1.61
24	8	96	26	8.66E+06	2.34E+06	148.84	142.47	31.57
25	10	224	75	1.62E+07	5.41E+06	343.49	115.48	15.51
26	10	130	35	9.38E+06	2.53E+06	160.29	143.31	27.38
27	8	122	45	1.10E+07	4.06E+06	257.62	104.91	18.37
28	10	134	33	9.67E+06	2.38E+06	151.13	156.51	30.51
29	18	176	54	7.05E+06	2.16E+06	137.40	125.92	19.68
30	8	90	33	8.12E+06	2.98E+06	188.92	105.53	21.54
31	8	96	19	8.66E+06	1.71E+06	108.77	194.17	48.85
32	8	132	13	1.19E+07	1.17E+06	74.42	384.45	111.91
33	6	113	21	1.36E+07	2.53E+06	160.29	206.59	49.19
34	8	69	24	6.22E+06	2.16E+06	137.40	111.20	26.41
35	6	116	24	1.39E+07	2.89E+06	183.19	185.86	41.78
36	8	113	24	1.02E+07	2.16E+06	137.40	181.12	40.80

LS3

Longitude (°):	21.9952
Latitude (°):	120.8650
Stratigraphic age:	12-11
Effective track density for fluence monitor (tracks/cm ²):	6.14E+05
Relative error (%):	3.94E-02
Effective uranium content of monitor (ppm):	39
zeta factor & standard error (yr cm ²):	127 5
Size of counter square (cm ²):	1.39E-06

crystal	Ng	Ns	Ni	rho-s (tr/cm ²)	rho-i (tr/cm ²)	U (ppm)	age (Ma)	±
1	12	96	42	5.77E+06	2.53E+06	160.29	88.56	16.44
2	12	75	30	4.51E+06	1.80E+06	114.50	96.81	20.96
3	7	110	45	1.13E+07	4.64E+06	294.42	94.67	16.82
4	8	105	33	9.47E+06	2.98E+06	188.92	122.96	24.61
5	6	131	56	1.58E+07	6.73E+06	427.45	90.63	14.54
6	10	180	65	1.30E+07	4.69E+06	297.69	107.14	15.59
7	10	61	24	4.40E+06	1.73E+06	109.92	98.41	23.76
8	8	163	33	1.47E+07	2.98E+06	188.92	189.88	36.36
9	8	52	18	4.69E+06	1.62E+06	103.05	111.73	30.60
10	8	145	43	1.31E+07	3.88E+06	246.17	130.24	22.70
11	8	109	35	9.83E+06	3.16E+06	200.37	120.37	23.46
12	9	94	32	7.54E+06	2.57E+06	162.84	113.60	23.31
13	8	126	50	1.14E+07	4.51E+06	286.24	97.57	16.38
14	10	103	30	7.43E+06	2.16E+06	137.40	132.58	27.58
15	6	147	30	1.77E+07	3.61E+06	228.99	188.39	37.85
16	6	74	13	8.90E+06	1.56E+06	99.23	218.34	65.75
17	12	153	40	9.20E+06	2.41E+06	152.66	147.53	26.30

18	12	186	72	1.12E+07	4.33E+06	274.79	100.01	13.97
19	10	110	37	7.94E+06	2.67E+06	169.45	114.96	21.92
20	12	68	11	4.09E+06	6.61E+05	41.98	236.78	77.03
21	8	64	34	5.77E+06	3.07E+06	194.64	73.02	15.54
22	8	85	39	7.67E+06	3.52E+06	223.27	84.48	16.39
23	10	156	23	1.13E+07	1.66E+06	105.34	259.33	58.06
24	10	139	46	1.00E+07	3.32E+06	210.67	116.83	19.95
25	6	122	34	1.47E+07	4.09E+06	259.52	138.49	26.94
26	18	68	23	2.73E+06	9.22E+05	58.52	114.33	27.63
27	8	55	25	4.96E+06	2.25E+06	143.12	85.27	20.61
28	8	93	30	8.39E+06	2.71E+06	171.74	119.82	25.23
29	6	66	16	7.94E+06	1.92E+06	122.13	158.96	44.36
30	6	105	38	1.26E+07	4.57E+06	290.06	106.91	20.31
31	6	62	19	7.46E+06	2.28E+06	145.03	126.07	33.11
32	6	99	32	1.19E+07	3.85E+06	244.26	119.58	24.39
33	9	147	50	1.18E+07	4.01E+06	254.44	113.69	18.69
34	8	47	4	4.24E+06	3.61E+05	22.90	442.85	230.76
35	8	224	53	2.02E+07	4.78E+06	303.41	162.82	25.00
36	15	114	40	5.48E+06	1.92E+06	122.13	110.24	20.33
37	6	76	36	9.14E+06	4.33E+06	274.79	81.84	16.61
38	6	90	26	1.08E+07	3.13E+06	198.46	133.65	29.83
39	6	120	41	1.44E+07	4.93E+06	312.96	113.19	20.55
40	8	129	55	1.16E+07	4.96E+06	314.86	90.86	14.70
41	8	49	10	4.42E+06	9.02E+05	57.25	188.39	65.44
42	10	101	31	7.29E+06	2.24E+06	141.97	125.87	25.92
43	6	40	14	4.81E+06	1.68E+06	106.86	110.52	34.36
44	12	172	109	1.03E+07	6.55E+06	416.00	61.27	7.56
45	6	132	84	1.59E+07	1.01E+07	641.18	61.02	8.57
46	6	77	50	9.26E+06	6.01E+06	381.65	59.80	10.90
47	8	123	19	1.11E+07	1.71E+06	108.77	247.74	61.19
48	16	185	64	8.34E+06	2.89E+06	183.19	111.80	16.30
49	14	87	47	4.48E+06	2.42E+06	153.75	71.82	13.05
51	6	57	24	6.85E+06	2.89E+06	183.19	92.00	22.43
52	8	111	39	1.00E+07	3.52E+06	223.27	110.10	20.56
53	6	90	25	1.08E+07	3.01E+06	190.83	138.94	31.48
54	10	199	49	1.44E+07	3.54E+06	224.41	156.53	25.08
55	12	301	29	1.81E+07	1.74E+06	110.68	392.73	76.60
56	7	86	29	8.86E+06	2.99E+06	189.74	114.67	24.69
57	6	47	18	5.65E+06	2.16E+06	137.40	101.07	28.06
58	6	118	36	1.42E+07	4.33E+06	274.79	126.63	24.19
59	10	129	42	9.31E+06	3.03E+06	192.35	118.73	21.17
60	10	156	113	1.13E+07	8.15E+06	517.52	53.64	6.68
61	6	64	6	7.70E+06	7.22E+05	45.80	403.27	172.29
62	6	99	34	1.19E+07	4.09E+06	259.52	112.61	22.45

Data repository item 3.

Table DR2. Detrital U-Pb age data for samples from Lilongshan and Loshui

Sample	Grain	U (ppm)	Th/U	% Com Pb	$^{206}\text{Pb}/$ ^{238}U	2 σ	^{207}Pb $/^{235}\text{U}$	2 σ	$^{207}\text{Pb} /$ ^{206}Pb	2 σ
LL1	G1	630	0.50	1.23	226.1	5.4	234.5	8.5	306.8	28.8
	G2	303	0.31	1.63	227.1	5.7	247.1	12.3	480.7	38.3
	G3	593	0.44	6.59	12.2	3.3	28.3	4.0		
	G4	409	0.41	0.65	183.4	4.9	187.0	8.6	199.6	39.1
	G5	561	0.35	0.64	1755.6	34.9	1809.0	82.5	1881.5	11.4
	G6	106	0.42	1.24	138.8	5.2	146.1	13.4	491.9	82.5
	G8	531	0.20	0.51	1686.7	33.6	1772.3	82.7	1883.8	11.9
	G9	364	0.05	0.70	1600.8	31.9	1716.4	85.5	1902.4	12.3
	G10	253	1.00	1.82	133.7	4.4	147.5	8.6	465.4	50.1
	G11	383	0.47	0.90	233.4	5.7	236.6	10.8	333.1	36.4

	G12	448	1.11	3.11	232.0	5.7	249.2	11.8	462.2	36.4
	G13	293	0.12	0.93	1888.7	38.7	1883.6	109.5	1916.6	12.5
	G14	508	0.21	1.09	184.9	4.8	194.8	7.7	361.4	32.1
	G16	692	2.14	2.92	18.9	3.3	24.5	3.6		
	G17	281	0.24	0.79	1906.9	39.5	1920.2	125.1	1967.3	12.8
	G18	392	0.15	0.62	1758.3	36.0	1810.7	100.9	1873.3	13.0
	G19	455	0.52	2.37	10.9	3.3	13.8	3.6		
	G21	242	0.29	1.02	193.8	5.2	196.7	9.4	319.8	39.7
	G23	143	0.51	1.49	178.5	5.0	180.3	9.2	343.3	43.0
	G24	71	0.45	2.50	1912.1	41.5	1820.3	188.2	1891.0	16.0
	G25	262	0.38	0.62	173.1	4.9	169.1	8.5	190.8	43.5
LL2	G1	61	0.83	-0.51	1976.9	39.1	1794.9	182.4	1785.9	15.3
	G2	138	1.02	-2.44	537.3	10.5	521.2	25.7	580.3	27.3
	G3	108	0.89	-0.94	1806.8	34.9	1782.9	155.7	1809.5	14.8
	G4	65	0.82	-0.77	2567.9	52.9	2358.7	308.2	2345.4	13.7
	G5	46	0.92	-0.65	980.9	20.7	891.4	78.4	998.3	29.4
	G9	363	0.60	-1.59	237.6	5.7	236.6	8.9	241.7	28.3
	G8	252	0.67	-1.74	462.6	9.2	451.7	18.3	456.7	25.2
	G13	196	0.28	1.77	492.2	10.8	524.9	30.6	777.2	31.3
	G16	355	0.41	0.60	259.4	6.8	263.8	13.7	328.4	39.6
	G17	173	0.61	1.82	779.1	15.8	775.8	42.3	889.1	22.7
	G19	153	0.50	1.31	2857.2	63.0	2790.0	386.8	2833.0	11.5
	G21	481	0.72	-0.11	227.4	6.1	247.4	9.7	518.0	28.9
	G24	106	0.47	1.62	2415.8	52.1	2328.0	261.6	2365.1	12.8
	G26	389	0.32	0.50	1886.9	39.9	1863.3	170.3	1831.5	15.3
	G29	235	0.58	0.32	498.0	10.5	474.1	21.4	477.9	27.6
	G30	794	0.18	1.12	155.6	5.2	168.8	6.8	384.3	28.9
	G31	291	2.44	-4.15	132.6	5.2	134.6	9.2	245.8	59.2
	G33	361	0.66	0.78	172.5	5.6	176.0	9.2	290.7	42.7
	G34	94	0.55	1.60	1841.9	43.9	1742.0	266.1	1802.7	23.2
	G36	1417	0.20	0.16	187.5	5.6	188.1	7.6	171.1	31.0
	G37	166	1.23	-1.54	360.7	7.8	345.8	17.8	366.9	35.3
	G39	373	0.86	-0.28	240.1	6.4	240.1	10.5	287.2	33.7
	G40	315	2.72	-4.18	243.5	6.8	257.8	14.8	465.8	43.5
	G43	483	1.00	-0.01	2554.9	57.8	2525.5	290.6	2519.1	15.1
	G44	363	0.99	-0.38	251.2	6.6	258.9	11.2	358.9	32.6
	G48	117	0.62	0.02	853.3	15.5	812.2	37.1	850.2	19.2
	G49	251	0.93	-0.44	215.7	5.4	234.5	9.1	486.9	29.0
	G51	59	0.56	1.29	924.1	17.3	851.7	50.9	926.9	22.1
LS1	G1	127	0.49	1.50	446.2	4.3	444.1	23.3	626.1	30.5
	G2	365	0.29	0.44	1839.3	0.8	1849.7	107.1	1855.2	11.5
	G5	233	0.45	0.81	127.5	1.7	138.3	8.3	408.6	47.9
	G6	37	0.72	6.12	2156.7	3.0	2113.9	409.0	2260.8	17.2
	G8	303	0.80	-0.38	1658.2	1.5	1735.0	91.9	1870.6	11.5
	G10	357	0.29	0.31	1879.8	2.7	1911.9	132.1	2024.8	11.6
	G11	189	0.47	0.43	1994.2	1.3	1933.0	120.9	1917.2	11.4
	G12	234	0.58	0.08	1751.2	1.5	1778.3	107.6	1846.9	11.8
	G13	304	0.38	0.04	792.5	1.6	786.8	32.2	819.6	17.8
	G14	58	0.40	2.42	1916.8	2.2	1809.7	203.5	1883.6	14.8
	G15	254	0.48	0.10	322.6	0.7	321.5	12.9	400.4	27.8
	G17	323	0.53	-0.02	750.8	1.3	741.6	32.8	836.8	19.1
	G19	275	0.36	0.13	250.4	3.4	255.5	10.3	343.7	29.6
	G22	130	0.51	0.14	1713.2	1.8	1629.9	126.5	1666.1	13.9
	G24	99	0.63	1.88	805.9	0.7	850.5	53.6	1152.0	22.0
	G25	307	0.39	0.23	2227.6	1.5	2231.6	147.0	2261.4	10.7
	G26	191	0.85	-0.12	135.1	0.7	130.6	7.7	163.5	49.0
	G27	337	0.24	0.22	1758.3	1.0	1759.8	95.6	1841.3	11.6
	G28	188	0.48	1.06	149.4	1.2	155.1	8.6	356.8	44.8
	G29	142	0.62	1.11	113.2	2.1	106.5	7.3	116.9	57.7
	G30	207	0.71	1.25	138.2	0.9	148.5	8.9	357.6	48.5
LS3	G31	76	0.50	1.57	289.1	2.8	305.3	20.8	580.7	47.0
	G32	98	0.74	1.30	846.1	2.8	828.5	44.7	943.2	20.5
	G33	154	0.29	0.81	223.8	0.7	225.1	10.9	358.9	37.2
	G35	347	0.41	0.44	1969.6	3.8	1936.1	106.0	1879.7	11.2
	G1	146	1.01	1.32	127.5	5.6	123.8	11.0	138.7	82.4
	G2	125	0.61	1.39	139.5	5.8	136.9	11.5	238.1	76.2
	G5	940	0.43	1.02	2227.1	46.0	2314.6	138.8	2365.0	11.5
	G8	170	0.37	1.53	823.6	16.9	825.6	49.5	919.2	23.5
	G9	136	0.61	1.57	128.9	5.8	127.9	11.8	229.5	84.3
	G10	430	0.77	1.93	133.2	5.3	153.3	8.1	551.9	39.4
	G12	163	1.28	2.05	136.0	5.7	151.6	11.7	469.7	66.0
	G14	144	0.45	0.53	174.4	6.0	173.9	11.6	299.0	56.9
	G16	129	0.61	1.31	1760.8	35.4	1686.8	122.7	1757.3	13.9
	G17	142	0.64	0.36	278.2	7.3	256.6	14.4	276.1	44.0
	G21	172	0.50	0.70	120.8	5.3	121.7	8.8	341.6	61.3
	G23	121	0.46	0.70	269.4	7.3	258.5	15.9	356.4	47.8
	G24	392	1.29	-1.89	141.2	5.4	142.6	7.6	257.5	41.0

G25	238	0.66	0.27	196.0	6.3	201.0	13.7	318.1	56.2
G26	50	0.91	0.53	150.0	6.3	146.7	15.3	396.3	95.8
G27	89	0.68	2.94	135.2	6.4	139.5	16.6	494.2	107.9
G28	195	0.42	0.54	174.3	5.8	176.9	9.7	306.4	44.1
G31	208	0.58	0.56	247.6	6.9	262.5	14.0	472.1	40.2
G32	281	0.72	0.48	178.9	5.8	196.8	9.4	503.5	36.0
G35	458	0.24	0.75	1530.9	31.0	1654.0	86.2	1854.9	13.5
G39	341	0.61	0.46	241.6	6.7	244.4	11.8	300.3	37.3
G40	576	0.53	-0.08	184.4	5.8	185.6	8.1	267.7	32.8
G41	138	1.45	0.47	246.6	7.3	241.4	16.0	385.2	52.3
G42	136	0.90	0.39	252.0	7.5	253.2	17.9	377.7	55.4
G45	596	0.28	0.67	2203.4	46.7	2194.3	144.8	2216.7	12.8
G46	451	0.63	0.63	131.8	5.4	134.5	7.6	213.9	44.3
G47	114	1.11	1.29	846.0	17.7	785.0	43.7	804.8	23.9
G48	193	1.14	0.22	241.0	6.7	238.3	11.6	318.1	37.8
G50	249	0.44	1.81	138.9	5.6	143.1	9.9	268.6	58.4
G51	206	0.81	1.14	133.9	5.5	137.9	8.9	321.5	53.1
G52	395	0.66	1.06	236.1	6.6	237.6	10.4	297.7	33.1
G53	246	0.26	0.49	1967.5	43.4	1915.0	205.9	1882.9	16.6
